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DROP TESTS TO SUPPORT WATER-IMPACT AND PLANING BOAT DYNAMICS THEORY

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The occupants of high-speed planing boats are exposed to repeated shock impacts that result from hull slamming during operation in heavy seas. An important component of the research necessary for developing shock reduction technology is two-dimensional water-impact theory. Drop tests provide data necessary for evaluating shock reduction concepts, and for developing and validating two-dimensional theory. This report summarizes the method and results of an initial series of drop tests to baseline the water-impact characteristics of a rigid, high aspect-ratio, aluminum, prismatic hull model with 20-deg deadrise. Parameters varied during the baseline tests including drop height and weight. Comparison between the experimental data and CSS predictions, and recommendations for follow-on drop tests are given.

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FOREWORD

While operating in rough sea conditions, the occupants of high-speed planing boats are often exposed to extreme and repeated shock loads produced by hull/water impacts. The development of technology for reducing injury and discomfort will be greatly enhanced with improved water-entry and planing boat dynamics theory and simulation. A central component of many of these theories and simulations is two-dimensional water-impact theory. This report summarizes the first of a systematic series of drop tests performed at the Coastal Systems Station (CSS) to support development and validation of two-dimensional water-impact theory for planing boat hulls.

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INTRODUCTION

Occupants of planing boats, when operating at high speed in heavy seas, often impact waves with sufficient force to produce discomfort, loss in performance, and occasional injury. Examples of high speed planing boats operating in heavy seas include special operations craft of the U. S. Navy, Army, and Marines; Coast Guard search and rescue craft; offshore racing boats; high-speed offshore crew boats; and high-performance wave-runners and other personal watercraft.

Since the late 1980's the Coastal Systems Station (CSS), in support of the Office of Naval Research (ONR), has developed high speed planing boat shock reduction technology.[1-6] A lesson learned early during the research was that cost-effective development of shock reduction technology may be greatly enhanced with a nonlinear, multiple-mass, time-domain simulation of the planing boat, capable of dealing with a wide range of hull geometries and shock isolation concepts, and capable also of assessing human discomfort and injury.

A vital component of many evolving water-impact theories and most planing boat dynamic simulations is two-dimensional (2-D) water-entry theory. The drop tests summarized in this report provide a portion of the experimental data necessary to validate evolving 2-D water-entry theory. Follow-on drop tests will also be used to evaluate shock reduction concepts. An example of a 2-D water-impact code is the CSS simulation Water-Entry Dynamics and Injury Model (WEDIM).[3] WEDIM predicts acceleration, velocity, displacement, and human injury and discomfort resulting from a vertical water-impact of a multiple-mass, 2-D system with a prismatic hull.

The University of Michigan (UM) Naval Architecture and Marine Engineering Department has investigated water-entry and planing boat dynamics for many years. Beginning in 1995, CSS began a successful collaboration with UM to further planing boat shock reduction technology. In 1996, a portion of the CSS shock reduction research transitioned to the Gulf Coast Region Maritime Technology Center (GCRMTC) at the University of New Orleans (UNO). Participants in the ongoing GCRMTC shock reduction research include investigators at UM, UNO, and CSS, who are among the beneficiaries of the drop tests summarized in this report.

Vertical water-entry tests of wedges and prismatic hull sections have a long history. Example investigations include those of References 7, 8 and 9. CSS has conducted drop tests of various geometries since 1995 in support of the ONR shock reduction program.[4,6] The objective of these early CSS drop tests was to investigate the water-entry characteristics of a specific rigid hull geometry, corresponding to the U. S. Navy high speed assault craft.

The objective of the new drop test model and test series of FY 97 and beyond is to further support ongoing water-impact theory development, planing boat dynamics development, and

shock reduction concept evaluation, at GCRMTC/UNO, UM, CSS, and elsewhere. The intent of the initial FY 97 drop tests was to form the baseline dataset corresponding to the new drop test model.

The new model was designed to be light, rigid, and capable of modification for experimental evaluation of a broad range of geometries and shock reduction concepts of interest. The model is a high aspect-ratio, prismatic aluminum hull with a deadrise of 20 deg, designed for maximum rigidity and minimum weight. During the baseline tests described here, the model was dropped from three different heights and with three different weights. The model was instrumented with triaxial piezo-electric accelerometers for measurement of maximum accelerations, and triaxial piezo-resistive accelerometers for measurement of the acceleration time history. Above-water video photography provided general test documentation and qualitative confirmation of the submergence characteristics.

Follow-on drop tests, for FY 98 and beyond, are planned in support of several planing boat dynamics theory development and shock reduction research topics at GCRMTC, UNO, UM, and CSS. Planned investigations include deadrise variations for straight hull sections, non-straight hull sections, two-phase separated flow over hull strakes, nonsymmetric water-impacts, and evaluation of lower-hull shock isolation concepts.

TEST DESCRIPTION

The CSS drop test facility, drop test model, instrumentation, and test procedure are summarized in the following.

DROP TEST FACILITY

The tests were performed in the above-ground test pool in Building 319 at CSS. The test pool is a fresh water tank measuring 40 ft (12.2 m) in length, 15 ft (4.6 m) in width, and 12 ft (3.6 m) deep. An overhead crane and single-point quick-release hook were used to drop the test model to the water surface. The water temperature throughout the tests was 72 °F.

DROP TEST MODEL

The baseline drop test model, shown in Figure 1, is an aluminum prismatic hull with a deadrise of 20 deg (please note that all figures are found at the end of the report). A large model was selected to allow incorporation and investigation of lower-hull shock reduction concepts. The model has a length of 8 ft (2.44 m) and a beam of 2 ft (0.610 m). The chines were constructed

with a radius of 0.07 in. (0.18 cm). The radius of the keel is greater than desired, at approximately 1.5 in. (3.8 cm). The model includes a support bracket with a set of holes arranged in a circular pattern to allow future asymmetric drops of the model.

The empty test model was designed for minimum weight to allow investigation of a broad range of weight variations. The model weight was varied by securing lead bars to the bulkheads near the keel as shown in the figure. The model was also designed for maximum rigidity to reduce the contaminating effects of structural resonance. The intent was to assure that structural resonances occur in a bandwidth above that of water-impact phenomena and human biodynamics. In fact, these two design requirements are in competition and, as will be discussed further, complete elimination of high frequency structural dynamics within a lightweight aluminum model is not possible.

The aluminum model in its light condition, with instrumentation but without the addition of lead weight, weighs 269 lb (122 kg). The model in the middle-weight condition, with the addition of approximately one-half of the lead bars, weighs 641 lb (291 kg). The model in its heavy condition, with the addition of the remaining lead, weighs 1007 lb (457 kg). At 1007 lb, the drop model possesses sufficient reserve buoyancy to remain afloat with approximately 3 in. (7.6 cm) of freeboard.

ACCELERATION MEASUREMENT INSTRUMENT

The acceleration measurement device was an External Data Recorder (EDR), model EDR-3-50, manufactured by Instrumented Sensor Technology, Inc. (IST). The EDR unit is a self-contained triaxial accelerometer measurement device mounted within a rigid box measuring 4.4 by 4.2 by 2.1 in. (11.2 by 10.7 by 5.3 cm) and weighing 3.2 lb (1.45 kg). The unit contains piezo-resistive accelerometers with a full-scale range of +/- 50 g, with 0.1 g resolution, an inherent frequency response of 0 to 1050 Hz at -3 dB, and a resonant frequency of 1800 Hz. Firmware within the EDR unit processes the raw analog data from each accelerometer with a 10-bit analog-to-digital converter, and stores the result to RAM. The particular EDR-3-50 used for the drop tests, S/N 441, was equipped with a 290 Hz anti-aliasing filter, and was recalibrated by IST in early 1997. The firmware within the unit includes a *zero-drift* feature, forcing the recorded acceleration to slowly drift towards zero until the unit triggers, at which time the unit records acceleration relative to the value just prior to triggering. Following each trigger, the zero-drift feature is disabled for the duration of each event.

TEST PROCEDURE

The drop tests were conducted during the months of May and September 1997 in the CSS Building 319 Test Pool. Video photography of the fall, initial impact, and post-impact phase of each drop event was taken at 30 frames/sec. The video photography provided a history of the drop test program, the opportunity to confirm that the keel entered the water surface horizontally for each drop, and the opportunity to examine the general water impact and post-impact dynamics. In

addition, given the known video frame rate, an approximate displacement time history of the drop event may be reconstructed from the video for comparison to the displacement obtained by double integration of the acceleration data, or for comparison to the predicted displacement time history.

The splash produced during the higher drop heights often interferes with the view from the video camera. Thus a 5-ft (1.5 m) stave, constructed of lightweight PVC and marked in 3-in. (7.62 cm) increments, was mounted vertically to the side of the model to facilitate follow-on evaluation of the video record of the drop dynamics.

The EDR accelerometer unit was secured to the longitudinal strength member near the center of gravity of the drop test model. The unit was programmed to sample at 1000 Hz, and was programmed to store, in sequence, each impact event during which the acceleration exceeds the specified trigger level of +/- 1.0 g. Given the 290 Hz built-in anti-aliasing filter and the programmed 1000 Hz sampling rate, the EDR unit was capable of accurate acceleration measurements from 0 to 290 Hz. The data recorded by the EDR is not filtered further prior to internal recording. The digitized acceleration time histories were downloaded to a laptop computer and saved to disk at the completion of each set of measurements. Further filtering was performed by the investigators following the test.

The test model was fitted at a single point to the quick-release mechanism attached to the overhead crane by a shackle. The model was lifted to the required height by the crane and dropped onto the center of the water surface. The model was dropped from heights of 2, 4 and 6 ft (0.610, 1.22, and 1.83 m), measured from the keel to the water level. The weight variations were 269, 641, and 1007 lb (122, 291, and 457 kg). Each height and weight variation was repeated three times to assure repeatability. The time interval between each drop was sufficient to assure a motionless model, level keel, and smooth water surface.

MEASUREMENT RESULTS

The water-entry dynamics of interest includes the initial high-frequency impact phase and the longer-duration post-impact phase. The initial phase is of greatest interest for investigation of human injury, while both phases are important for investigating planing boat dynamics in waves. For example, in a planing boat dynamics simulation, the post-impact dynamics form the initial conditions for the launch of a boat off a wave and into the airborne condition.

Impact-Phase Results

The unfiltered EDR acceleration time histories are shown in Figures 2, 3 and 4 with the time scale expanded to show the details of the impact phase. Figure 2 shows the impact-phase time histories at 269 lb for the three drop heights. Figure 3 shows the time histories at 641 lb for the three heights. Figure 4 shows the time histories at 1007 lb for the three heights. The expected

increase in measured acceleration magnitude with increasing drop height, and the expected decrease in acceleration magnitude with increasing weight, are both apparent in the figures. The figures also include the accelerations predicted by WEDIM, to be discussed later.

As seen in Figures 3 and 4, the data suggests the presence of high-frequency structural dynamics within the model, particularly for for the middle- and heavy-weight conditions. Any drop model structural dynamics that may be present are expected to be increasingly excited by the greater energy associated with increased weight. The resonant frequency, at nominally 140 Hz, is fortunately well above the 0 to 25 Hz bandwidth of human biodynamics.[10]

Figure 5 is the acceleration time history corresponding to the 4-ft drop of the medium weight model, with each sample point shown. This impact event displays a particularly high degree of structural dynamics. The figure illustrates that the 1000 Hz sampling rate discerns the 150 Hz structural dynamics.

Acceleration/Velocity/Displacement Extended Time History Results

The full acceleration time histories measured by the EDR unit are shown in Figures 6, 7, and 8, corresponding to the three model weights. Shown also in the figures are the velocity and displacement, obtained by numerical integration of the acceleration data. The pre-release and free-fall phases of the acceleration time histories of Figures 6, 7, and 8 were forced to 0 g and -1 g, respectively. The measured deviation from zero during the pre-release phase in the raw acceleration time history (seen in Figures 2, 3, and 4) is on the order of 0.06 g, produced by the finite accelerometer noise floor. The small drift towards zero from -1 g during the free-fall phase in the raw acceleration time history (seen in Figures 2, 3, and 4) was produced by the zero-drift feature of the EDR unit. While these adjustments to the acceleration data of Figures 5, 6, and 7 were very small, they assured that the integrated velocity and displacement most accurately reflect the actual drop dynamics.

The loss in velocity during the impact phase, as shown in Figures 6, 7, and 8, is of considerable interest. The reduction in velocity during the impact phase of the light model is seen to be about 2/3 of its pre-impact value, while the reduction in velocity for the heavy model is closer to 1/3. If the model weight were to have been much lower than that of the light condition, the velocity reduction would be full and the accelerations would become extreme. If the model weight were to have been much higher than that of the heavy condition, both the velocity reduction and the impact accelerations would approach zero. The displacement time histories shows that the hull penetration increases with both drop height and model weight, as expected.

Figure 6, 7, and 8 illustrate an interesting feature of the post-impact phase. In each of the time histories, a high frequency resonance is seen at about 350 msec following the impact. During each of the water impacts, the investigators clearly heard a *ker-plunk* sound as the model entered the water. Observation during the drops, and post-test viewing of the video, revealed that the *ker* sound is produced by the impact of the keel with the water, and the *plunk* is produced as the model reaches its maximum depth. Typically, as the model sinks, the displaced water flows rapidly

upwards and around the hull, violently impacting its flat upper surface just as the model is at maximum depth, and producing the loud sound. The upper surface of the model may possess a structural resonance with a frequency corresponding to that seen in the data typically 350 msec after the initial impact. The physical phenomena that produced the audible *ker-plunk* during the drop tests are believed to be somewhat analogous to those that produce the similar sound often heard when a stone is dropped into the water. While this result is interesting, it is not very relevant to the boat dynamics problem, because a boat generally does not fully submerge during impacts with waves. The most useful and relevant portion of the time histories is that prior to the time of maximum submergence.

The effect of filtering and of filter algorithm selection, for a representative EDR acceleration time history, was investigated briefly by processing the unfiltered data with four different digital low-pass filters, at corner frequencies of 25 and 100 Hz. The 25 Hz frequency was chosen because, as stated earlier, the bandwidth of human biodynamics is generally accepted to be below 25 Hz. The 100 Hz corner frequency was chosen because this frequency is below the observed model structural dynamics, at around 140 Hz, but preserves most of the high-frequency dynamics associated with the initial water-impact phase.

Figures 9 and 10 summarize the filtering results. The unfiltered acceleration time history measured by the EDR, for the 641-lb, 4-ft drop event, is shown at the top of each figure. The next four plots within each figure are the corresponding filtered time histories produced by the 2-pole Butterworth, 5-pole Butterworth, 2-pole Chebyshev, and 5-pole Chebyshev digital filters. Small differences between the filters are seen in both the magnitude and phase shift of the filtered time history.

PREDICTIONS

The CSS code WEDIM simulates the vertical water-impact, submergence, and re-emergence of a 2-D, prismatic, elastic hull segment. The code includes a post-processor for assessing the possibility of human injury and discomfort. The injury assessment option is most appropriate for WEDIM predictions involving drops of full-scale hulls or full-scale hull sections.

The WEDIM code includes a three degree-of-freedom simulation of the vertical dynamics of three vertically arranged masses. The dampening component between the lower two masses is represented linearly, while the stiffening component may be specified nonlinearly. The WEDIM calculation involves simultaneous integration of three differential equations, each equation describing the vertical motion of the three masses. The force produced on the lower prismatic hull during the water-impact is predicted within WEDIM by the original added mass theory of von Karman.[11] The aspect ratio correction within WEDIM, to allow comparison of 2-D water-impact predictions to 3-D drop test data, is estimated with a simple expression for added mass of fully-submerged flat plates in heave, given by Paster and Abkowitz.[12]

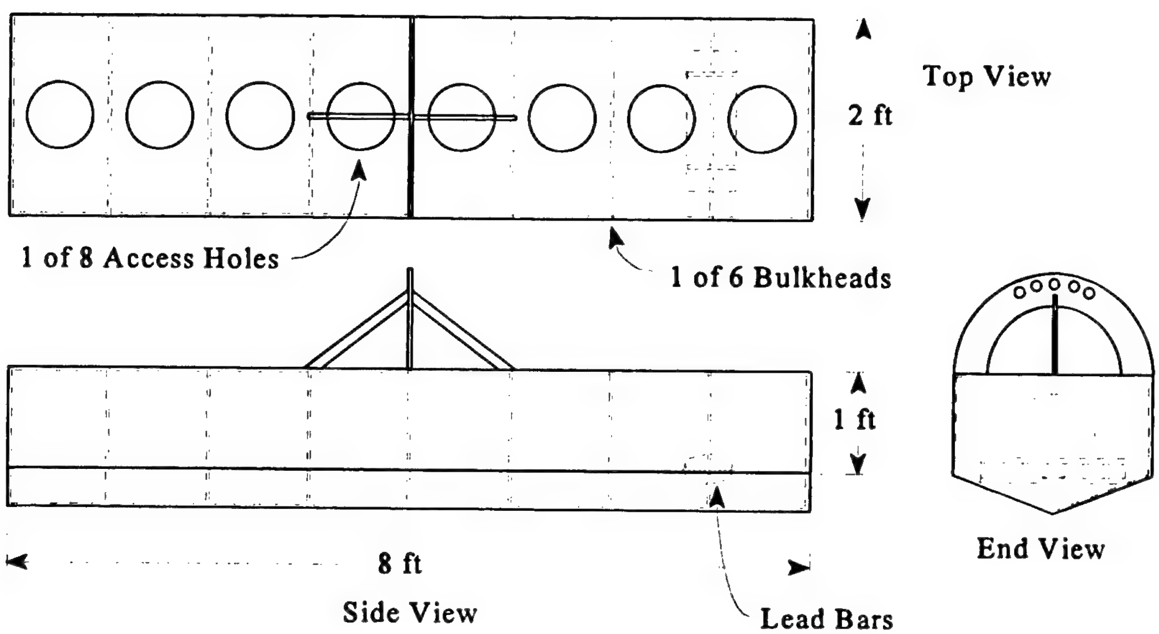
For the present comparison between the acceleration predictions of WEDIM, and those measured by the EDR unit, the three masses within WEDIM were combined into a single rigid mass to represent the drop test model. The comparisons between the WEDIM acceleration predictions and the EDR-measured accelerations are shown in Figures 2, 3, and 4. The comparison shows excellent agreement between the theory and data. Relative to the data, the theory generally shows a slightly greater pulse width with somewhat different shape characteristics on the down slope of the impact pulse.

SUMMARY AND RECOMMENDATIONS

An initial series of instrumented drop tests of a drop test model was conducted to provide water-impact data for validation of 2-D water-impact theory. The model was a high aspect ratio, prismatic aluminum hull with a deadrise of 20 deg. The model was instrumented with a three-axis piezo-resistive accelerometer set. The model was dropped over a range of weights and from various heights. The CSS water-impact code WEDIM was applied to the drop test conditions as an example comparison between theory and data. The comparison shows excellent agreement between theory and data.

Follow-on drop tests are planned for investigating the water-impact characteristics of variations in deadrise, non-straight hull sections, two-phase flow over strakes, asymmetric impact conditions, and acceleration isolation concepts.

1/4-inch Aluminum Construction, 20 deg Deadrise



269 lb Empty; 641 and 1007 lb With Added Lead

Figure 1. Drop Test Model

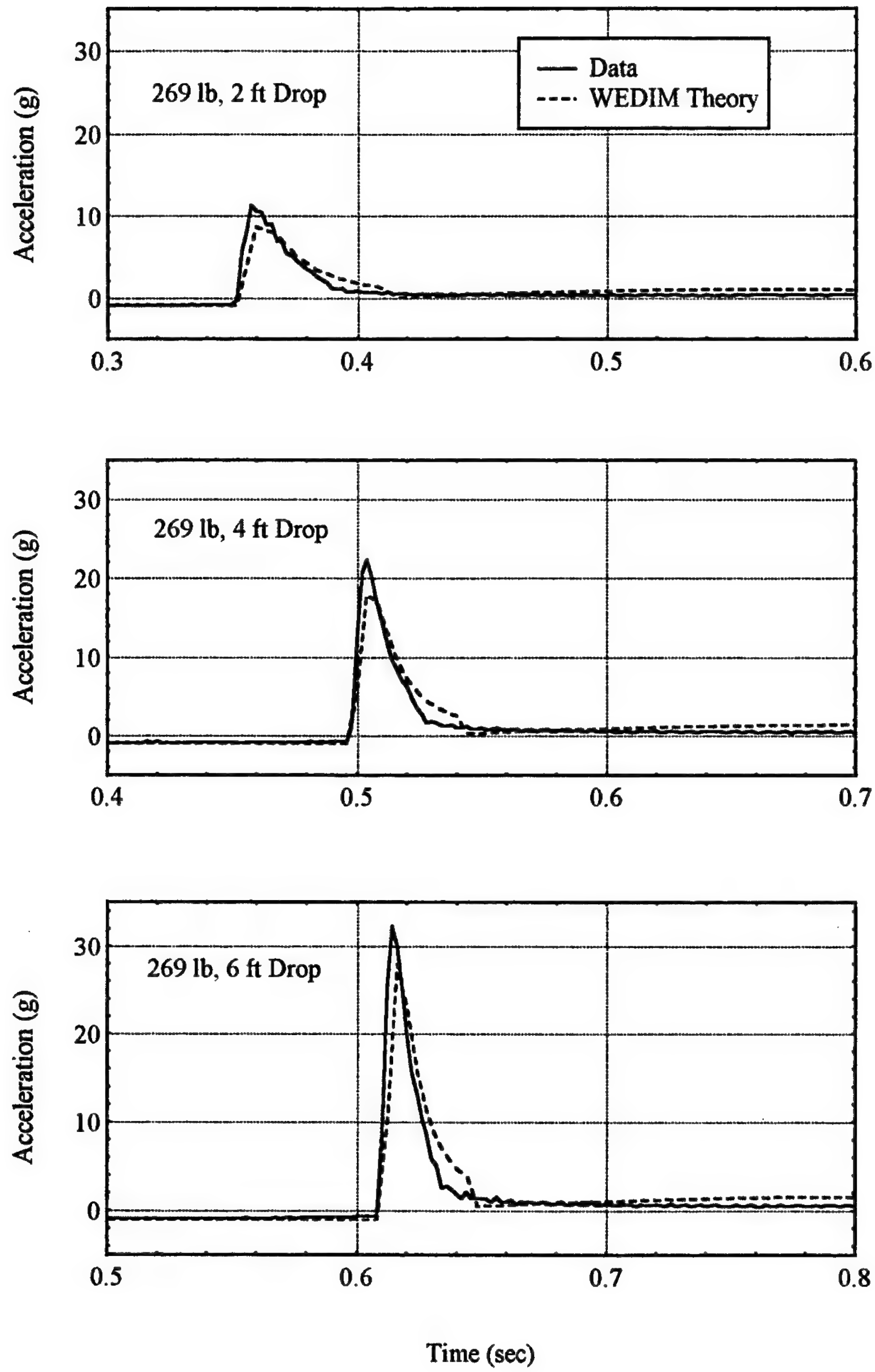


Figure 2. Measured (EDR, Unfiltered) and Predicted
Acceleration Time Histories, Light Condition

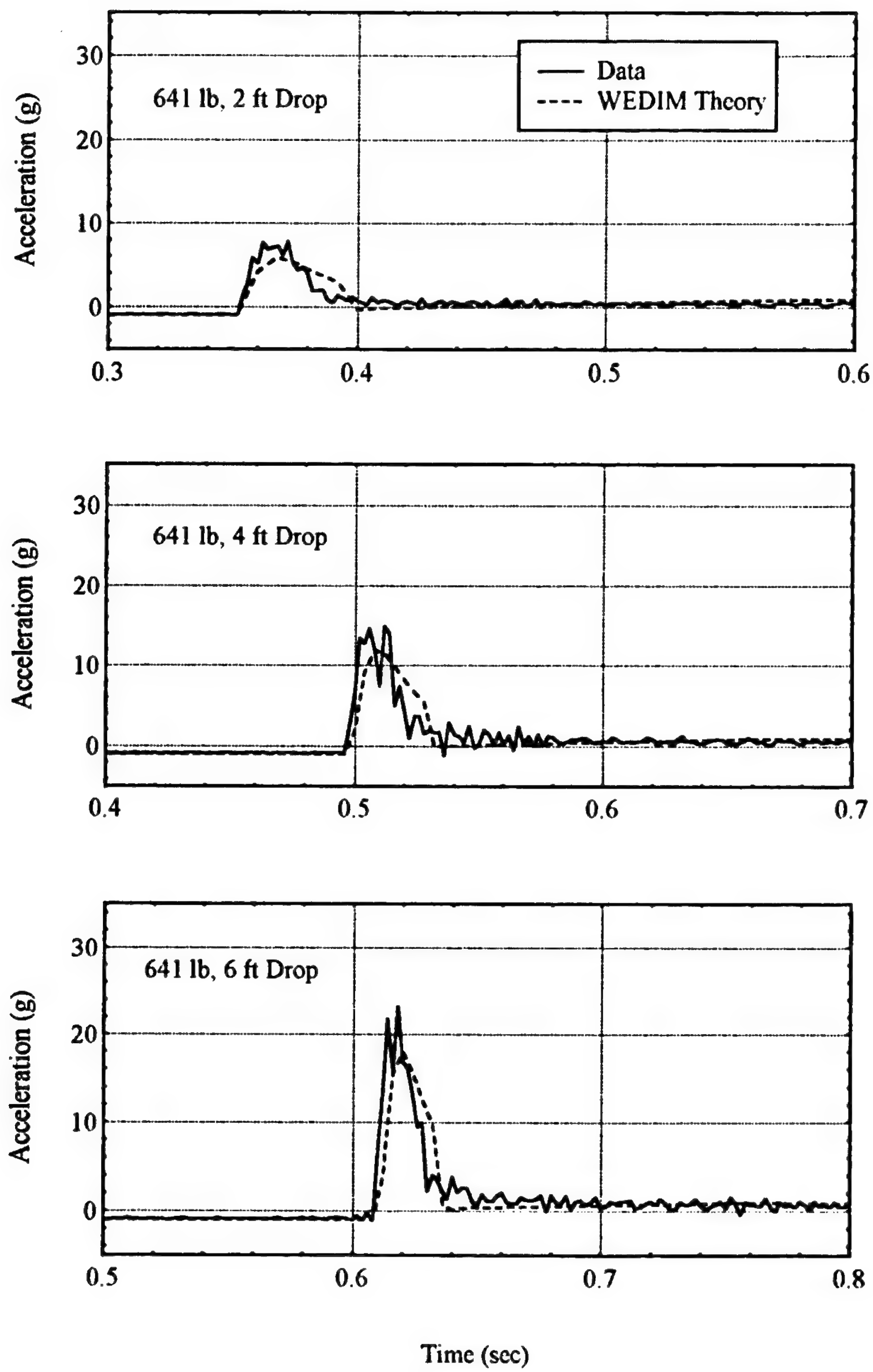


Figure 3. Measured (EDR, Unfiltered) and Predicted Acceleration Time Histories, Medium Condition

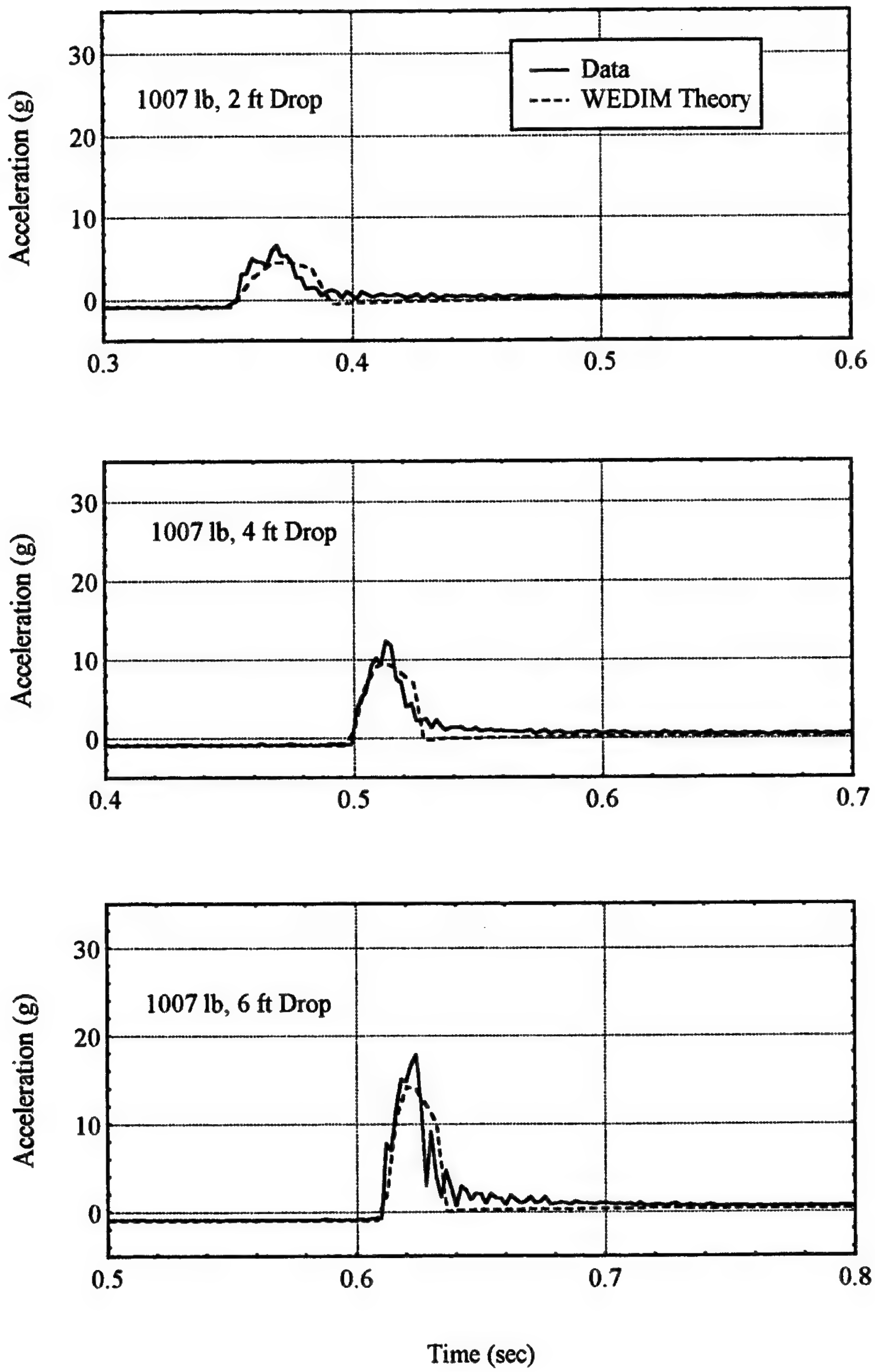


Figure 4. Measured (EDR, Unfiltered) and Predicted
Acceleration Time Histories, Heavy Condition

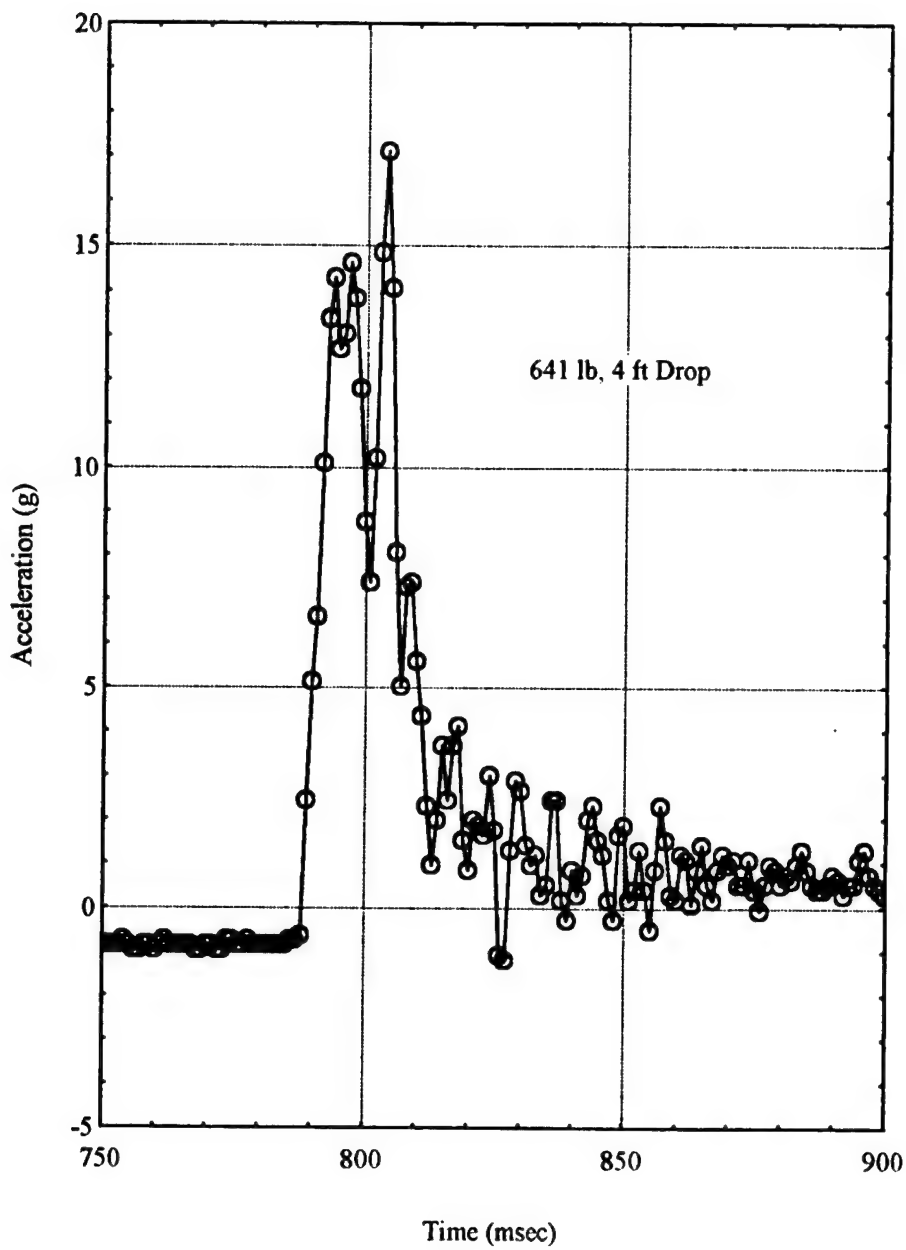


Figure 5. Sample Points for 4-Ft Drop, Medium Condition

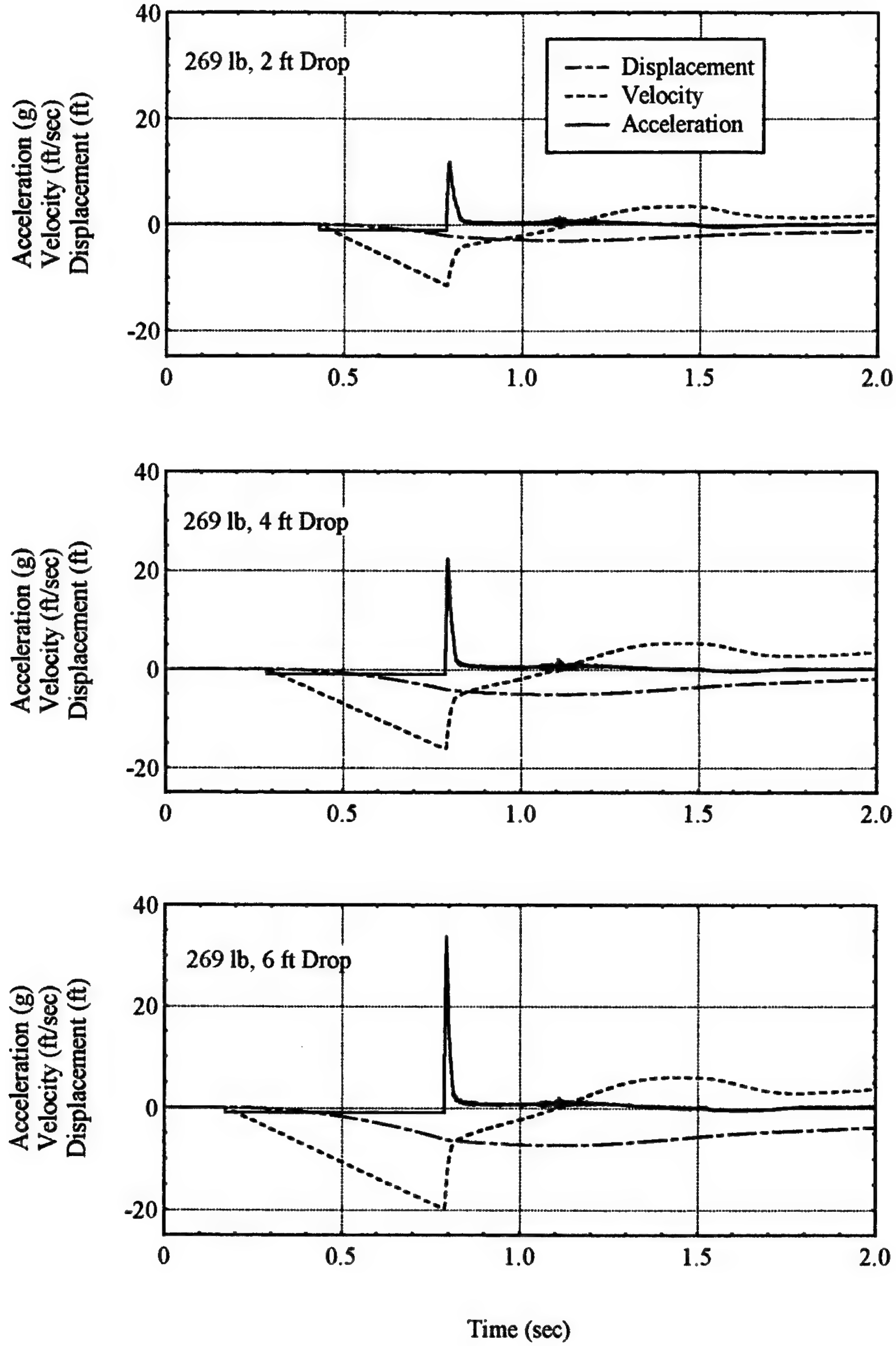


Figure 6. Measured (EDR, Unfiltered) Acceleration,
Velocity, and Displacement Time Histories, Light Condition

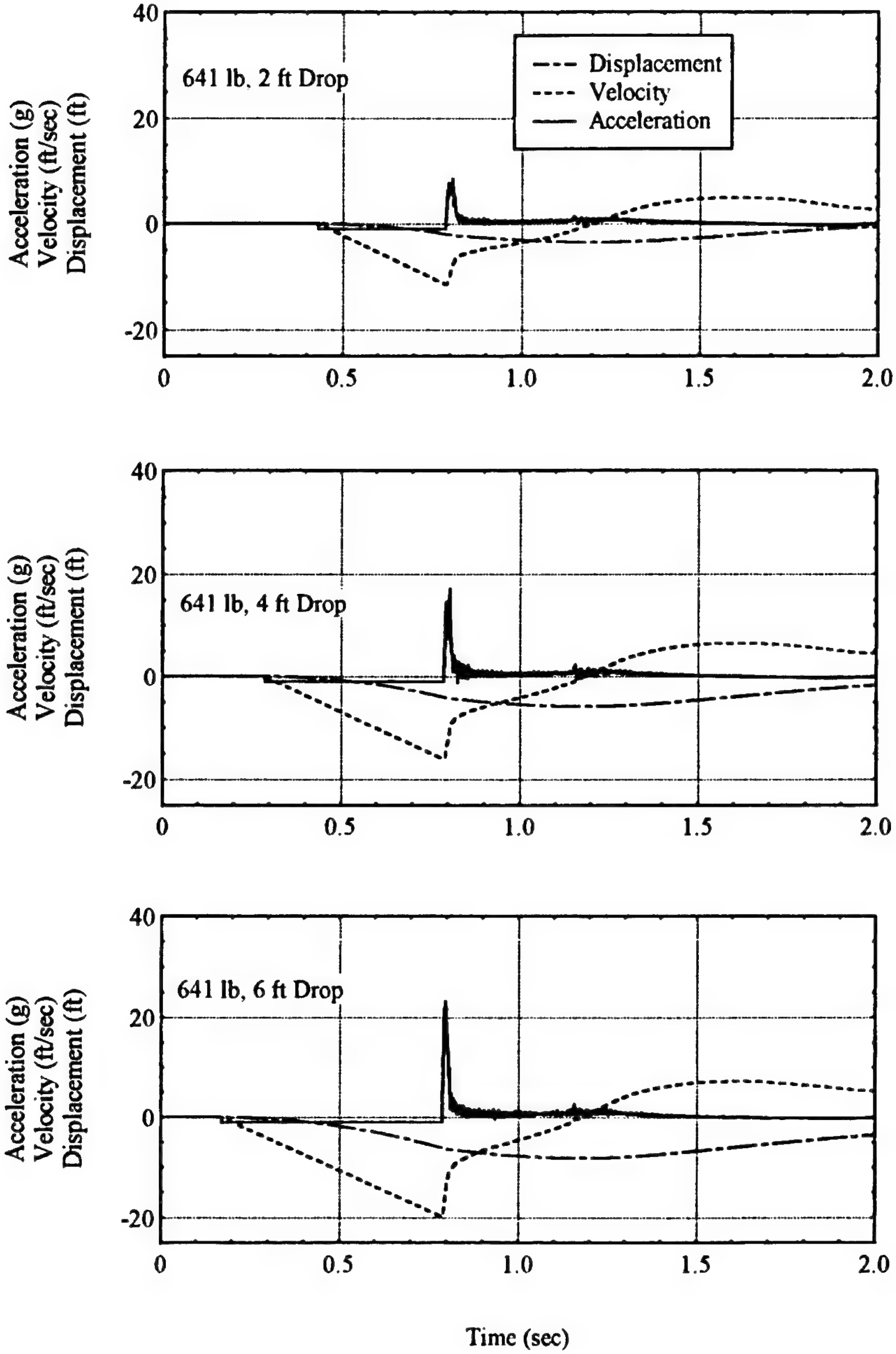


Figure 7. Measured (EDR, Unfiltered) Acceleration, Velocity, and Displacement Time Histories, Medium Condition

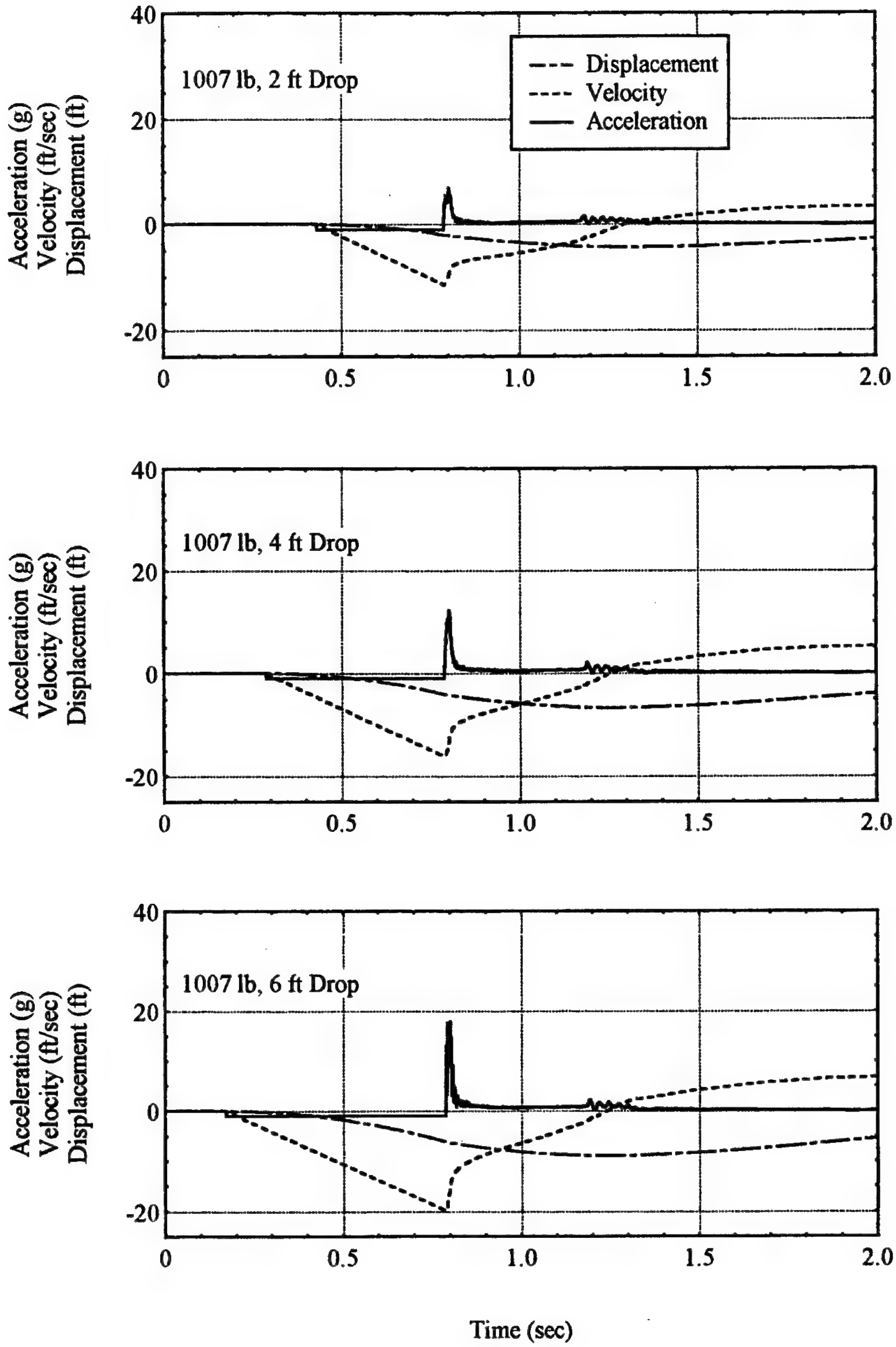


Figure 8. Measured (EDR, Unfiltered) Acceleration, Velocity, and Displacement Time Histories, Heavy Condition

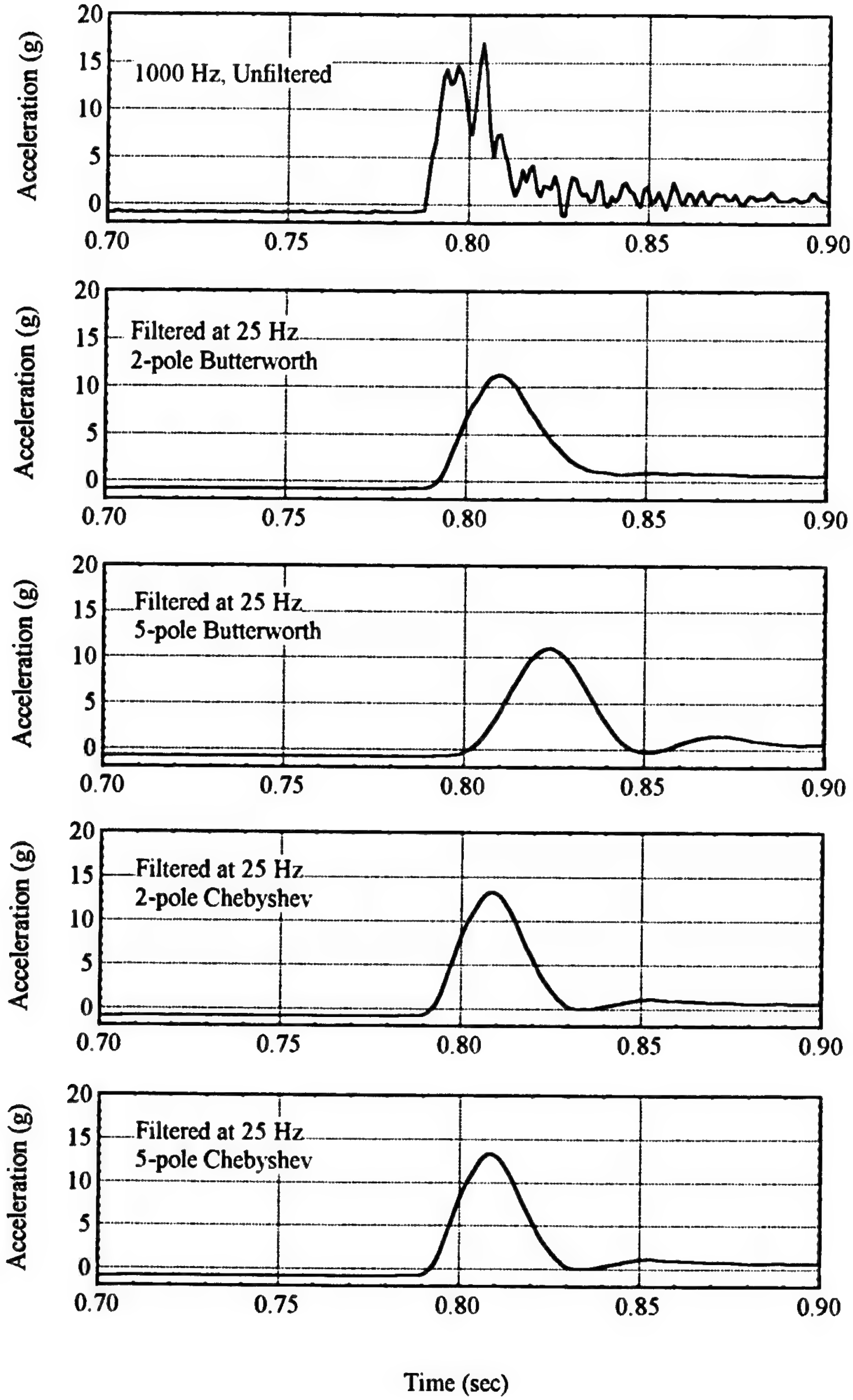


Figure 9. Filtered Acceleration Time History, 25 Hz

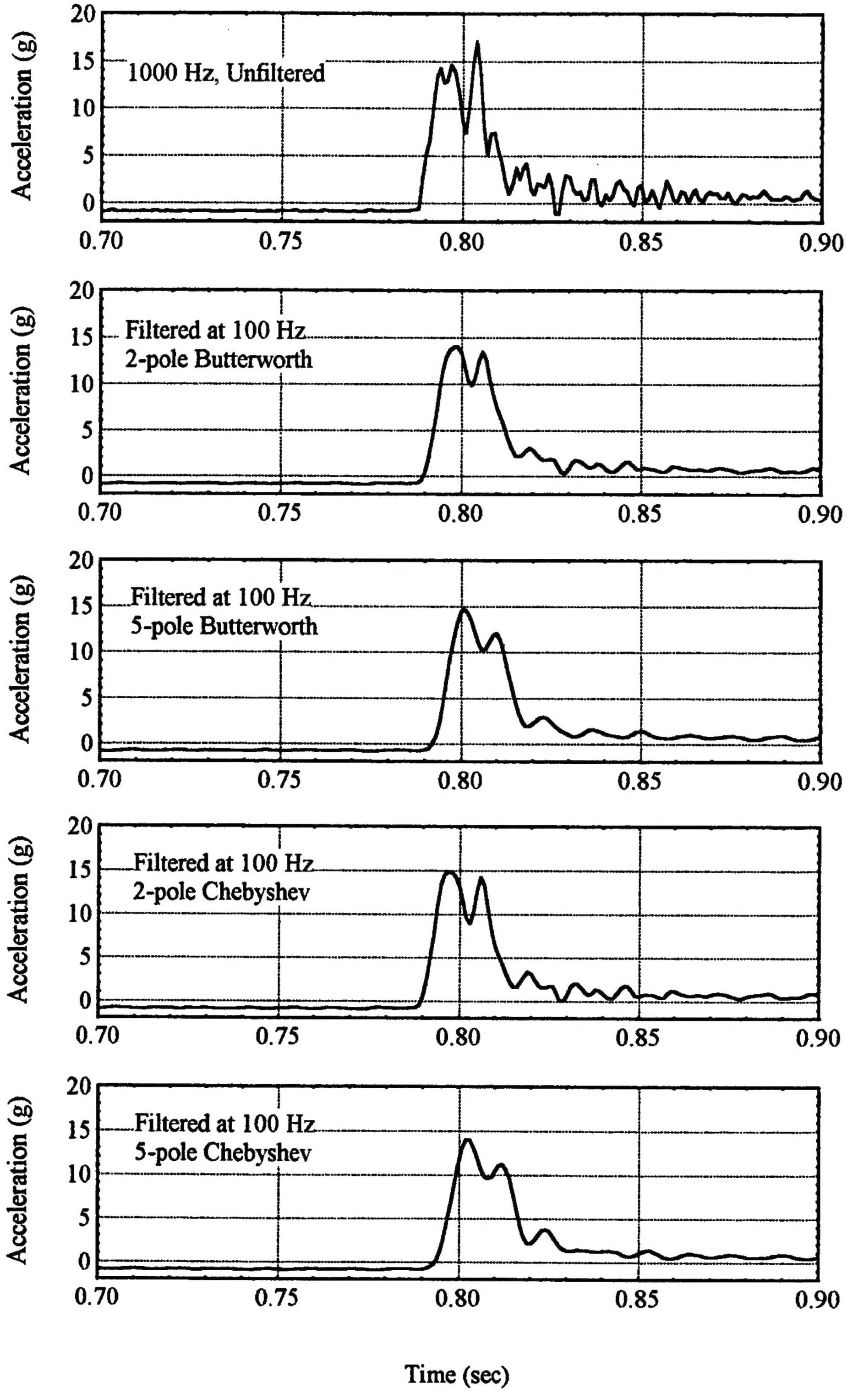


Figure 10. Filtered Acceleration Time History, 100 Hz

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